A 5,730-Hr Cyclic Endurance Test Of The SPT-100

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ABSTRACT

A cyclic endurance test of the Russian 1.35 kW Stationary Plasma Thruster SPT- 100 is described. The endurance test was performed for 6,925 on/off cycles and 5,730.3 hours of operation at an input power to the thruster of 1.35 kW. Each cycle was approximately 50 minutes of thruster on-time and 23 minutes of thruster off-time. Thruster efficiency decreased from 50% to 42% as the thruster aged over the first 1,000 hours. The efficiency increased slowly over the next 1,000 hours and then slowly decreased to 45% by the end of the wear test. The unused cathode igniter and radiation shields were found to erode at an unexpectedly high rate. A short between the cathode emitter and cathode igniter occurred at cycle 5,316; the short was cleared without opening the vacuum tank but the short reoccurred at cycle 6,344. The vacuum chamber was opened after the thruster had accumulated 6,346 cycles and 5,250 hours of operating time to clear this short and repair the thrust stand, which had failed at cycle 5,818. The wear test was continued and voluntarily terminated when 5,002.5 hours of operation were accumulated on cathode # 1. Data from this wear test indicate that the likely first failure mechanism for this thruster design is shorting between the igniter and cathode emitter in the unused cathode. The endurance test was performed under a cooperative program between Space Systems/Loral, JPL, and the Ballistic Missile Defense Organization (BMDO).

INTRODUCTION

Stationary plasma thrusters (SPT) are gridless ion thrusters that were originally developed in the US. in the early 1960's. [1-3] Although efforts in the U. S. to develop high thrust efficiencies failed, efforts in the former U.S.S.R. were quite successful. The SPT was successfully developed during the 1960's and 1970's by Morozov[4] and others[5,6] to obtain a unique combination of specific impulse and efficiency. More than 50 SPT-70 thrusters have flown in space, starting with the Meteor I in 1969- 1970.[7,8] More recentl y, eight SPT- 100 thrusters were flown on the Russian GALS television satellite to perform both north-south and east-west station-keeping functions.[9]

In 1991 a team of electric propulsion specialists visited the former U.S.S.R. to experimental y evaluate the performance of a 1.35-kW SPT at the Scientific Research Institute of Thermal Processes in Moscow and at Design Bureau "Fakel" in Kaliningrad, Russia.[10,11] The evaluation verified that the actual performance of the thruster was close to the claimed performance of 50% efficiency at a specific impulse of 1600 s. [10] Studies indicate that for north/south station keeping and Earth orbit raising applications of electric propulsion, the optimum specific impulse is in the range of 1,000-2,000 sec. *[2] The combination of the flight heritage of the SPT-70 and the availability of thrusters and thruster data led to substantial interest in these thrusters by Western spacecraft manufacturers for primary and auxiliary propulsion appl icat ions.

Space Systems/Loral is presently flight-qualifying SPT- 100 thrusters for north/south station keeping and Earth orbit raising applications and plans to provide these thrusters on their spacecraft. [13] At Design Bureau "Fakel", a steady-state life test was performed [14], and performance, plume and EMI/RFI evaluations were conducted at NASA Lewis Research Center. 15-18

A key aspect of the SPT-1OO evaluation program was characterization of the long term operating behavior of the thruster. Typical mission applications of interest require operating times of several thousand hours. Potential use of the thruster for north-south station keeping of commercial communication satellites will also require the capability for several thousand on/off cycles. To address these objectives a cyclic endurance test was performed at JPL under a cooperative program between Space Systems/Loral, JPL (under the JPL Affiliates program) and the BMDO. The original goal for the test was to accumulate a total of 5,000 hours and 6,000 cycles on the thruster; the test was extended to 6,925 cycles and 5,730 hours to accumulate more than 5,000 hours of operating time on a single cathode. Several papers describe the wear test results through the first 5,000 cycles. [1]9-21 This paper describes the results of this cyclic endurance test for 6,925 cycles and 5,730.3 hours of operation at 1350 watts.

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APPARATUS

The Russian SPT- 100 plasma thruster used in this endurance test is shown in Fig. 1. This thruster as tested comes with two hollow cathodes and a xenon flow control system (XFC) enclosed in a box directl y behind the SPT- 100 (Fig. 2). The outer insulator which forms the outside discharge chamber wall is approximately 100.8 mm-dia. In this endurance test the cathode at the top (cathode #1) was used as the primary cathode.

The SPT- 100 thruster endurance test was performed in a 3.1-m dia. x 5.1-m stainless steel vacuum chamber equipped with three each, 1.2-m diameter helium cryopumps. The minimum no-load tank pressure was observed to be 4.2 x10-6 Pa (3.2 x 10-8 Torr). The rated pumping speed for the three pumps combined is 81,000 liters/s on xenon, however the measured pump speed on xenon is approximately 50,000 1/s.

The thruster was mounted near one end of the vacuum tank, directly facing a cryopump which is positioned at the other end of the vacuum tank. The discharge chamber surfaces of the SPT thruster consist of insulator materials, and it has been demonstrated that the performance of SPT thrusters can be significantly affected by the deposition of a conducting coating on the insulator.[22] To protect the cryopump and minimize the amount of material sputtered back to the thruster, the facility was lined with graphite, and a graphite beam target was constructed. The beam target consists of 6.4-mm thick graphite panels arranged in a chevron configuration and placed as shown in Ref. 19. Graphite was selected as the target material because of its low sputter yield at the ion energies expected from the SPT.[23] The chevron configuration results in large angles (typically greater than 50 degrees) between the expected ion trajectories and the direction normal to the graphite surface, which may both reduce the graphite sputter rate and reduce the amount of sputtered material directed back towards the thruster. A photograph of the SPT- 100 mounted inside the vacuum chamber is shown in Fig. 2.

Due to the beam divergence characteristics of the SPT- 100, material can be sputtered from the vacuum tank sidewalls and deposited onto the thruster. Therefore the cylindrical side walls of the vacuum chamber were also lined with graphite panels. Glass slides were placed 21 cm to either side of the SPT thruster such that material back sputtered to the SPT could be quantified and characterized.

Tank pressure was measured using two ion gauges. One gauge tube was mounted directly to the outer wall of vacuum tank; the other tube was mounted inside the vacuum tank, approximately 0.51 m above and 0.58 m behind the SPT- 100. This tube was calibrated on xenon and nitrogen using a spinning rotor gauge that is traceable to NIST.

The propellant system for supplying xenon to the SPT- 100 thruster is described in Ref. 19. The system was constructed from 0.64 -cm-dia stainless-steel tubing that was scrubbed with acetone and alcohol before assembly. Prior to operating the SPT, the propellant system was checked for dew point, hydrocarbon contamination, and particulate contamination. The xenon supply pressure was indicated by a capacitance manometer that was calibrated to an accuracy of ±0.25% at 249.94 kPa, the nominal working pressure for the SPT- 100. This pressure was then dropped to the level required by the cathode and discharge chamber within the xenon flow control system (XFC) that is an integral part of the SPT- 100 and is located directly behind it in the vacuum system. Therefore the pressure in the propellant tubing was above atmospheric pressure up to the SPT XFC. The purity of the xenon used by the SPT was tested directly from the xenon bottle. Purity data indicate that the specifications (99.999%) were exceeded.

A thermal mass flow meter was used to measure the total propellant flow rate. The flow meter was calibrated on both nit rogen and xenon by the manufacturer using a primary calibration standard, and at JPL using a bubble volumeter. The nitrogen calibration performed at JPL agreed with the primary standard calibration to within 1% for all flow rates tested. The bubble volumeter data on xenon were curve fit and the. curve fit was incorporated into the SPT data acquisition and control program.

A xenon recovery system was used to recover and store xenon consumed by the SPT- 100 and is described in Ref. 19. A probe rake, consisting of 25 Faraday probes of diameter 2.3 cm, mounted on a semicircular arc 2.4 m in diameter was used to examine the thruster exhaust plume. The probe buttons were biased to -23 volts when used to measure ion current in the plume. The probe rake was positioned such that the thruster is at the center of the semicircular arc; the axes of the rake were aligned with the plane formed by the outer insulator of the SPT- 100 such that the rake can be pivoted around a line normal to the thruster axis. This configuration enables complete hemispherical profiles of the exhaust plume to be made. When the probe rake is not in use, a motor rotates the rake to a position of approximately 90 degrees with respect to the thruster axis.

The SPT- 100 was mounted to an inverted pendulum style thrust stand of the type developed at NASA LeRC;[24] in this design, thrust is indicated by a linear voltage displacement transducer (LVDT). The thrust stand is surrounded by a water-cooled housing to minimize temperature effects on the measured thrust; the housing can be seen just below the SPT-100 in Fig. 2. The thrust stand inclination was adjusted continuously by computer to improve the accuracy of the thrust measurement over extended test times. Thrust stand calibrations were performed in-situ throughout the life test using a set of weights. Norman y 15 or more data sets were performed in order to obtain a large enough sampling for statistical analyses. Statistical analyses of the calibration data was also used to determine the best thrust stand inclination setting. Repeatability of the calibrations were normally 1.0% or better.

The thruster was operated with a bread board power conditioning unit (PCU) developed by Space Systems/Loral. The SPT- 100 discharge current and magnetic field current were adjusted by supplying the appropriate voltage input signal to the PCU. The PCU output voltage was fixed at approximately 300 V. Propellant flow rate was controlled by the SPT- 100 flow control unit which is part of the thruster; the mass flow rate was determined by the discharge current setting. The PCU was turned on and off by supplying the appropriate digital signal to the PCU. Once the engine parameters were adjusted and the PCU was turned on, the SPT- 100 thruster was started and operated automatically by the bread board PCU. The PCU/thruster sequencing is described in Table. I for one complete cycle.

Table 1. PCU/Thruster Sequencing For One Complete Cycle

Time sec	Action
o	PCU start command received from computer
10	Cathode heater, capillary current, magnetic field current on
170	Cathode igniter voltage applied; cathode heater off.
171	SPT achieves 1.5 A discharge; run time clock started, begin on-phase
180	SPT achieves 4.5 A discharge
3180	SPT turned off by stop command issued by computer; begin off-phase
4380	PCU start command received from computer for next cycle

Steady-state thruster operation, start-up and shutdown sequencing were controlled by a PC based data acquisition (DAC) system. This system also monitored the vacuum facility enabling unattended operation. A total of 56 channels that include thrust, xenon mass flow rate, anode voltage and current, floating voltage, magnet current, cathode heater current, thermothrottle current, SPT inlet xenon pressure, tank pressure and various other facility components were monitored and recorded as a function of time. The data were averaged in real time and the averaged values were displayed on a monitor screen. The data were recorded on the computer hard disc drive every 30-60 seconds.

The computer issued the PCU start and stop commands. If certain engine or facility parameters exceeded specifications, the computer sent the PCU stop command to the PCU, opened a relay between the PCU and its power source, and activated a telephone dialing machine (autodialer). The computer sent a change-of-state signal every 15 seconds to an electronic timer (heartbeat box); in the event of a computer failure, the timer activated a series of relays to turn off PCU power, xenon flow, and activates the autodialer.

PCU telemetry for various SPT- 100 currents were calibrated to values obtained from calibrated current shunts. The discharge current calibration was determined using a voltmeter which averages the direct-current value of the discharge current shunt voltage drop over a period of four seconds Oscillations in the discharge current were obtained with an inductive probe placed on the discharge current cable close to the vacuum tank feed through. The discharge voltage ripple was measured at the vacuum tank feed through as well, using a combination inductive/Hall effect probe. Cabling length between the feed through and SPT is approximate] y 6 m. After cycle 663 of the cyclic life test the RMS value of the discharge current was measured using a true RM S voltmeter.

The thruster was photographed (from an off-axis view) periodically through a window in the vacuum system to document the condition of the thruster. Insulator thicknesses were determined from photographs by measuring the ratio of insulator width to the outer diameter of the outer insulator or inner diameter of the inner insulator. An off-axis view of the SPT-1OO is shown in Fig. 3. The SPT-100 can be seen operating in the endurance test facility in Fig. 4.

PROCEDURE

The SPT- 100 was purged with xenon when the mechanical pumps were used to pump the vacuum tank from atmosphere to 50 mTorr. The SPT- 100 was operated only if the vacuum tank pressure indicated by the calibrated ion gauge reads below 2.7 x 10^{-5} Pa (2x 10^{-7} Torr). During a facility shutdown (cryopumps off) the SPT-100 was purged with xenon.

A cycle is defined as any time the thruster achieves a discharge current of> 1.5 A. The first 26 cycles of the life test were used to test the data acquisition and control program, the facility, and the probe rake; in these cycles the thruster was operated for varying time periods, from less than one minute to over 60 minutes, and at varying discharge currents

The computer performed the task of starting and stopping the thruster, taking data, and monitoring the facility. Oscilloscope traces of oscillations in the discharge current and AC ripple in the discharge voltage were obtained approximately every 10 cycles. Approximately every 200 hours the life test was interrupted for a short period of time to photograph the thruster, measure flow meter zero drift, and to re-calibrate the thrust stand (T/S). Approximately every 200 hours a probe scan was obtained using the probe rake.

RESULTS AND DISCUSSION

DESCRIPTION OF WEAR TEST CYCLES

Thruster operating hours vs. cycle number is plotted in Fig. 6. Starting with cycle 27 the SPT-100 was cycled for 50 minutes on and 20 minutes off, with 3 minutes for cathode pre-heating. The SPT- 100 completed 6,925 starts and 5,730.3 hours of operation; of these, 103 cycles totaling 32.73 hours were not operated for the standard 50 minutes because of testing requirements, computer/facility failures, operator error, or to computer-commanded shutdowns. There were no shutdowns required due to abnormal SPT operation. In all cycles the SPT always performed to its nominal operating condition of 1.35 kW. Non-standard cycles are categorized in Table II.

Table II. Test/shutdown descriptions

Shutdown Description	Number of Shutdowns
Thruster/DAC testing	33
PCU/PCU input power supply failures	22
Cryopump failures	20
Computer/DAC errors or hardware failures	16
Operator-induced shutdowns	8
Cycle stopped manually, thruster emitting sparks	2
Power grid transients	2
TOTAL	103

A total of 33 cycles were operated at various time intervals to test the thruster or DAC system. Twenty-two shutdowns were commanded by the computer due to PPU module failures or PPU input power supply failures; the discharge voltage decreased up to 6 volts when a PPU module failed. Twenty shutdowns were due to cryopump failures. The shutdowns were commanded by computer when a cryopump failed and vacuum tank pressure exceeded 0.013 Pa (104 Torr), or when a cryopump temperature sensor failed. Tank pressure did not exceed 0.04 Pa during these failures. Xenon flow through the SPT was maintained when a cryopump was turned off.

Hardware failures consisted primarily of xenon regulator pressure failures or cryopump cooling water failures. Computer/DAC failures consisted of printer failures, software crashes and loose cabling. Operator-induced shutdowns consisted of various actions resulting in a computer-commanded shutdown.

WEAR TEST SIGNIFICANT EVENTS

A glow in the non-operating cathode was observed beginning in cycle 1. This SPT-100 thruster utilizes a propellant system with no absolute flow shut-off to the unused cathode.[25] Newer designs include positive flow shut-off to the unused cathode. The glow in the unused cathode is visible in a photograph (Fig. 5) of the SPT-100 in operation. The brightness of the glow appeared to decrease with time.

Unexpectedly high igniter wear rates in the unused cathode (cathode #2) were observed soon after the start of the wear test. On cycles 5,316 and 6,344 the cathode igniter shorted to the cathode emitter. Two other failed thruster start attempts at cycles 561 and 6,879 were attributed to other, non-thruster causes that can be summarized as follows: no start signal sent by computer, start signal not received by PPU, or PPU igniter start circuit failure.

Between cycles 1,545-1,744 a thrust stand calibration weight was inadvertently left deployed on the thrust stand, therefore no thrust measurements for these cycles are available. Ten minutes after the completion of cycle 2675 an earthquake shook the thrust stand hard enough to cause the middle 3-gram mass in the thrust stand calibration system to slip down to the end 3-gram mass. Therefore only two masses, 3 grams and 9 grams, could be used for thrust stand calibrations until after cycle 6,346, when the vacuum tank was opened and the thrust stand was repaired. After cycle 5,817 a software error in the DAC program caused the thrust stand tilt motor to jam at it's extreme position, therefore between cycles 5818-6346 no thrust measurements were possible. The tilt control assembly was repaired simultaneously with the calibration weights.

After cycle 5,661 one of the cryopumps failed completely. The wear test was continued with only two cryopumps operating until the pump was repaired after cycle 6,176. Therefore, the tank pressure between cycles 5,661-6,176 was 2.5x) 0-3 Pa (1.9 x 10^{-5} Torr), compared to the usual 1.9 x 10^{-3} Pa (1 .45 x 10^{-5} Torr). It was not necessary to open the vacuum tank to repair the cryopump. After the pump was repaired the tank pressure returned to the normal load pressure of 1.9 x 10^{-3} Pa.

TEST DATA FOR CYCLES 26-6925

Engine parameters such as efficiency, discharge current and voltage, thrust and specific impulse for cycles 26-6,925 are shown in Figs. 7-10. Thruster data were analyzed to determine cycle-to-cycle changes in thruster operating characteristics. Thrust was determined by subtracting the LVDT voltage four minutes after the SPT was turned off from the LVDT voltage obtained from averaging LVDT voltage over the last ten minutes of the cycle, and multiplying by the appropriate thrust stand calibration factor. Efficiency and specific impulse were calculated using the values for thrust, mass flow rate, and engine power (including magnet power), averaged over the last 10 minutes of the cycle.

Larger variations in thruster parameters such as floating voltage and thrust occurred in the first 900 hours of thruster operation than in the rest of the test. In most cases the variations were intentionally induced by applying supplementary current to the magnet coils to investigate thruster performance and oscillations in the discharge current and voltage.

Discharge Voltage

Discharge voltage is plotted as a function of thruster cycles in Fig. 7. Discharge voltage was measured between the anode and cathode emitter. Between cycles 1-810 the discharge voltage was monitored via PPU telemetry; after cycle 810 the discharge voltage was measured using a voltage attenuator. Variations in discharge voltage observed through cycles 150-2,200 were due to PCU power supply input failures or PCU discharge supply module failures; without all modules functioning the engine discharge loaded down the PCU and the output voltage dropped approximately 6 V. Variations in discharge voltage observed through cycles 5,300-5,600 were due to placement of ammeters in series with the discharge; since the PCU output voltage was fixed, the impedance of the ammeters resulted in a small decrease in the discharge voltage.

Floating Voltage

Floating voltage is plotted as a function of thruster cycles in Fig. 7. Variations in floating voltage through approximately cycle 1,000 were due to intentional changes in the auxiliary magnet current. 19 Following that the floating voltage increased to a maximum at cycle 1,300, then decreased until approximately cycle 2,100. The SPT-1OO was operated on cathode #2 (the redundant cathode) at cycle 5,321, then again between cycles 5,352-6,196. The floating voltage was generally higher by 2.5-3 volts when the thruster was operated on cathode #2. The floating voltage also increased slightly when the thruster was operated with only two of the cryopumps functioning (cycles 5,661-6,176), which resulted in a 32% increase in tank pressure. As can be seen, there is little difference in the floating voltage between the start and end of the wear test.

Mass Flow Rate and Discharge Current

Mass flow rate and discharge current are plotted as a function of thruster cycles in Fig. 8. For a fixed mass flow rate of approximately 5.5 mg/s the discharge current decreased approximately 0.4% over 6,925 cycles. The thermal mass flow meter calibration drifted approximately 1% between run hour O- 1,740; in the data presented in Fig. 8, the mass flow indicated by the flow meter was adjusted with the assumption that the drift rate was uniform between run hour O-1,740.

Thrust, Efficiency and Specific Impulse

Thrust and efficiency are plotted as a function of thruster cycles in Fig. 9, and thrust and specific impulse are plotted in Fig. 10. The data indicate that the thrust decreased until app. cycle 1,000, whereupon the thrust began to increase until approximately cycle 3,000. Between cycles 3,000-6,925 the thrust decreased approximately 1.5-2 mN. At the end of the wear test the thrust was app. 81-82 mN, compared to 85 mN at the beginning of the test. The shape of the thrust vs. cycles curve is surprising and counter to expectations; it is not understood how or why the thrust increase occurred after cycle 1,000. However, the thrust data are qualitatively similar to data obtained from a steady-state endurance test performed by Fakel Enterprises.[14] Theoretical analyses of the thrust increase with time was presented in Ref. 14. Efficiency and specific impulse, of course, tracked the shape of the thrust curve; by the end of the wear test thruster efficiency had decreased to 0.45-0.46.

Discharge Current oscillations and Voltage Ripple

Oscillations in discharge current and voltage are shown in Fig. 11. The probes used to measure discharge current and voltage oscillations were positioned close to the vacuum tank feed through and downstream of the PPU output filter. There was approximately 6 m of cable length between the tank feed through and the thruster.

In Ref. 19 reduced current and voltage oscillation amplitudes were associated with improved thruster performance. Initially, discharge current oscillation amplitudes were generally less than 2 A p-p, and voltage ripple less than 2.5 V p-p. By cycle 1,100 (run time 890 hrs) current oscillation amplitudes were 10 A p-p, and up to 15 V p-p ripple in the discharge voltage. Oscillation amplitudes began to decrease at approximately cycle 2,500 (2,043 hrs run time). By cycle 6,925 current oscillation amplitudes were only 5 A p-p maximum and 10 volts p-p maximum for the discharge voltage, these values are similar to those obtained at the start of the wear test.

Plume Characterization

The current density measured by the center probe of the probe rake for two different cycles, cycle 759 and cycle 6,925, are compared in Fig. 12. There appears to be little change in the shape of the exhaust plume over 6,200 cycles and 5,?00 hours, except that the peak current density decreased approximately 8% relative to the current density near the start of the wear test.

Insulator Erosion

Erosion of the discharge chamber insulator surfaces was documental photographically y and is plotted in Fig. 13 as a function of run time. Results indicate an erosion rate that is approximately the same as reported in Ref. 26. The data in Ref. 26 were obtained from steady-state wear tests performed in the former Soviet Union. The data imply that there is no significant change in the wear characteristics of the SPT-1OO when it is operated in cyclic testing.

Wear characteristics of the SPT-1OO are shown in Figs. 14-19. In Fig. 18 the tip heater for cathode #2 is on. The dark material on certain locations of the SFT-100 may be uneroded deposits of graphite sputtered from the graphite beam target or boron eroded from the insulators and redeposited onto various locations on the thruster. The amount of back-sputtered graphite onto glass slides located near the thruster was measured using a profilometer; the data indicate that the back-sputter rate varied bet ween 6.6-7.6 x 104 urn/hour.

The photographic records of this wear test indicate that by approximately run hour 75 grooves had formed in the outer insulator; by run hour 2,189 the downstream metallic face of the SPT- 100 was just beginning to be eroded by ion bombardment because the outer insulator was worn flush with the thruster surface. Inner insulator erosion was somewhat asymmetric; at the end of the wear test the inner insulator was reduced in thickness to approximately 1 mm at the 12:00 o'clock position (the cathodes are at 8:00 o'clock and 10:00 o'clock), 0.5 mm across from the cathodes and at 6:00, and adjacent to the cathodes the thickness was essentially zero millimeters.

Cathode Erosion

Cathode #2 eroded considerably even though it was operated for only 890 cycles and 727.8 hours in this wear test, and was not operated at all until cycle 5,321. This was the most surprising and unexpected result of the wear test; data from previous tests conducted in the former Soviet Union were obtained with both cathodes being operated for an equal amount of time, and cathode erosion was assumed to occur in the used, not unused, cathode. However, photographic evidence obtained in this wear test are conclusive that in this thruster configuration it is the unused cathode that erodes at the highest rate.

Changes in cathode #2 can be seen in the photographs in Figs. 20-25. By cycle 358 (run time= 281.5 hrs) there were indications that cathode #2 was being eroded. In Fig. 20 the erosion appears as a light crescent at the top of the igniter. There is also a discoloration near the igniter orifice. The crescent-shaped area increased in size (Figs. 21-22) and there are indications of erosion in the igniters of both cathodes in a direction radially towards the discharge chamber. In Fig. 23 the front face of the igniter has been roughened and it appears that the whole face is being eroded. , By cycle 2,676 (run time = 2191.34 hrs) the igniter cover on cathode #2 wore through completely at approximately the 12:00 o'clock position (Fig. 24). By cycle 4,703 (run time = 3,882 hrs) the igniter face on cathode #2 had disappeared. In Fig. 25 the tip heater of cathode #2 is on.

The data indicate that ions coming from the region between the two cathodes eroded the front face of the igniter of the unused cathode, with the heaviest erosion occurring near the. top of the igniter. There was a plasma glow inside the unused cathode from the start of the test (Fig. 5) but it is unknown what the impact of the plasma inside the unused cathode was on igniter/cathode erosion. Since the igniters and emitters of both cathodes were connected together, it is difficult to understand the wear characteristics of the SPT-1OO cathode.s. Understanding, of the wear mechanisms is complicated by the propellant leak in the non-functioning cathode.

On cycle 5,316 (run time = 4392.7 hrs) a short developed between the emitter and igniter of cathode #2 and the thruster did not start. The short appeared to be due to accumulation of sputtered material that bridged the igniter to the cathode emitter radiation shields at the 7:00-10:00 o'clock position (Fig. 25). In the thruster configuration used for the wear te st the igniters and emitters of both cathodes are connected together, resulting in cathode #1 being shorted as well, and the thruster could not be started because of power drain to the igniter high voltage start supply. The thruster was allowed to cool to room temperature, and the following 5 thruster starts were successful. However, the short again developed on cycle 5,321 and the thruster could not be started. With a thruster temperature of approximately 20 degrees C, the isolation between the igniter and cathode emitter was 0.8 ohms.

To clear the short the tip heater of cathode #2 was heated to 11.5 A and the thrust stand was wiggled with the tip heat er cycled on/of f; this was the first time the tip heater on cathode #2 had been turned on. It was not necessary to open the vacuum chamber to perform the above procedures. After several iterations of the above described procedure the igniter/emitter isolation had increased to several hundred ohms with the redundant cathode's tip heater hot.

On cycle 5,321 the thruster was started on cathode #2 for the first time. The thruster started without difficulty, despite the fact that the cathode igniter was heavily eroded and the cathode emitter possibly contaminated with metal deposits from the nearby sputtering of the igniter and possibly the radiation shields. The thruster was operated for one cycle; these actions increased the isolation between the igniter and the emitter to 1.24 kohms (thruster cold). The thruster was operated for a total of 727.8 hours and 890 cycles on cathode #2.

A major technical goal of the wear test was to demonstrate 5,000 hours on a single cathode, hence thruster operation was switched back to the primary cathode (cathode #1) after 6,196 cycles and 5125.5 hours of operating time. The thruster started without difficulty and was operated on cathode #1 until cycle 6,344 (run time = 5,248.4 hrs), when a short again developed between the igniter and cathode emitter. The thruster was operated for two more cycles, then the vacuum chamber was opened to inspect the thruster and repair the thrust stand. This was the only time in the wear test that the vacuum chamber was opened to atmosphere. Venting of the vacuum chamber was performed using dry nitrogen.

A physical inspection of the thruster indicated that the short developed in the redundant cathode between the igniter and the cathode radiation shields via deposits at the 8:00 o'clock position. The short was cleared by scraping the deposits away with tweezers; in addition, the redundant cathode was separated electrically from the primary cathode by cutting the wire cable to the redundant cathode.

Thrust stand repairs were also performed: the tilt motor assembly was unjammed, the second weight was moved to it's proper location, and the tank was pumped down. Total time of thruster exposure to atmosphere was approximately 25 hours. The thruster was restarted on cathode #1 100 hours after exposure to atmosphere; the wear test was completed using cathode #1.

Thruster Characteristics For Cycle 6.925

Thruster operating characteristics for cycle 6,925 are shown in Figs. 26-28. Variations in thruster discharge voltage and current are due partly to noise in the data acquisition system; no variations in discharge current and voltage were observed in the panel meters, and the voltage input (for discharge current and voltage) to the DAC system was essentially a constant. The changes in thrust in the first 500 seconds indicated in Fig. 28 are due to changes in the thrust stand tilt and not to changes in thrust. The data in these figures indicate that in the last cycle of the wear test the thruster operated and performed very well.

Post-Test Inspection

Photographs of the SPT- 100 thruster new and after 6,925 cycles and 5,730.3 hrs are shown in Figs. 29-32. The most striking features concerning erosion in this thruster are: complete erosion of the downstream end of the outer insulator, erosion of the downstream face of the thruster body, and erosion of the igniter in cathode #2..

Post-test inspection of the thruster revealed that the outer insulator was eroded completely away at the downstream face. At various locations the outer insulator was eroded completely through; at these locations the thruster body was eroded by discharge chamber ions. Deep lines and trenches characteristic of SPT insulator erosion marked the leading edges of the insulator (Fig. 31). The inner insulator thickness at the downstream end varied with position, as described previously.

A black deposit upstream of the erosion zone covered the interior walls of both the inner and outer insulators (see Fig. 20); the deposit was primarily boron, with some silicon, oxygen and a trace amount of xenon. The anode was covered by a very light film deposit (not yet analyzed); the electrical resistance across this film was measured using a flat electrode with a diameter of 2.5 mm that was pressed flat onto the anode. The resistance across the film varied between 0.8- 1.2 ohms and was a minimum diagonally across the cathodes and a maximum near the cathodes.

The downstream face of the thruster body was eroded as a ring approximately 2 mm deep. Pits were eroded into the thruster body at locations underlying those areas of the outer insulator that had eroded completely away. Through-holes were eroded completely into the thruster body at the four locations adjacent to the electromagnets, with the largest hole 1 mm x 7 mm long and located at the 1:30 o'clock position. At the 11:30 o'clock position there is a crescent-shaped hole in the thruster body that is 0.5 mm x 13 mm. The holes at the 4:30 o'clock and 7:30 o'clock positions barely go through the thruster body. Screw heads or screw ends at various locations on the face of the thruster body show signs of erosion (Fig. 31). The thruster face was covered with a metallic deposit that was heaviest between the 8:00-11:00 o'clock positions (cathode #1 is located at 9:30 o'clock and cathode #2 at 8:30 o'clock). The deposit consisted primarily of molybdenum, the same material used for the igniter.

A metallic layer was observed spalling off of the electromagnets that are located next to the cathodes. Analysis indicates that the metal film is primarily iron and nickel. No films were observed on the other two electromagnets located across from the cathodes at 1:30 o'clock and 4:30 o'clock positions.

The igniter of cathode #l showed evidence of direct impingement by ions coming from the discharge chamber. In Fig. 32 the wear pattern on this igniter begins at 12:00 o'clock and ends at 6:00 o'clock. The front face of the igniter has shallow grooves. Analysis of metal deposits on the outside surface of this igniter indicates that the material is primarily molybdenum and iron. The igniter orifice of cathode #1 increased in diameter, from a circle of approximately 6.3 mm dia to an ellipse of dimensions 9 x 10 mm; the side of the igniter orifice facing away from the SPT-100 eroded the most.

Inside the igniter of cathode #1 a small metallic deposit formed at the 9:00 o'clock position (Fig. 32). The cathode orifice diameter increased, from 1.2 mm at the start of the test to a chamfered surface of diameter 1.6 mm at the end of the test. A crystalline deposit was formed near the downstream end of the cathode orifice. The small sliver of material located inside the cathode spalled from an undetermined location after the thruster was removed from the vacuum chamber and transported by vehicle to another location to be photographed.

The downstream face of the igniter for cathode #2 was completely destroyed; metallic deposits were observed on the igniter at 6:00 o'clock-9:00 o'clock. The multi-layer cathode radiation shields also eroded at a high rate; in Fig. 32 only a section of a radiator shield between 1:00 o'clock and 5:00 o'clock remains. A large aggregate of material at the 9:00 o'clock position shorted the igniter to the cathode emitter radiation shields, which are at cathode potential.

A summary of post-test documentation is shown in Table 111. Total impulse in this table was calculated by multiplying the end-of-cycle thrust of each cycle by the run time for that cycle, and adding the impulse of each cycle to determine the total impulse delivered by the thruster. For cycles where no thrust was measured, the thrust was estimated.

Table 111. Wear Test Summary

Wear Test Started		July 1, 1993
Wear Test Completed		Nov 19, 1994
Total Thruster Operating Time	(Hrs)	5730.3
Operating Time on Cathode # 1	(Hrs)	5002.5
Operating Time on Cathode #2	(Hrs)	727.8
Total Number of Cycles		6925
Total cycles on Cathode #1		6035
Total Cycles on Cathode #2		890
Total Estimated Impulse	(N-s)	1.7X106
Back sputter Rate to Glass Slides	(10^{-4}um/Hr)	6.7-7.6

Parameter	Units	Cycle 26	Cycle 6925
Discharge Voltage	(V)	298	298
Discharge Current	(A)	4.5	4.7
Mass Flow Rate	(mg/s)	5.45	5.45
Floating Voltage	(V)	-15	-14
Thrust	(mN)	85	82
Efficiency		0.5	0.46
Current Oscillations Max	(A p-p)	6	5
Current Oscillations Typ	(A p-p)	2	2
Voltage Oscillations Max	(v p-p)	2.5	5
Voltage Oscillations Max	(V p-p)	5	10
Cathode #l Igniter Dia	(mm)	23.7	23.7
Cathode #1 Ign Orifice	(mm)	6.3	9X1O
Cathode #1 Orifice	(mm)	1.2	1.6
Anode-Cathode Isolation	(Mohms)	>40	>40
Igniter #l-Cathode Isolator	(Mohms)	>40	7.79*
Magnet Coil Resistance	(ohms)	0.49	0.50
Cathode #1 Heater	(ohms)	0.22	0.28+
Anode-SPT Connector	(ohms)	<0.1	0.8-1.2.
Thruster Mass	(grams)	5091	5015

* Isolation measured at room temperature
\+ Probable measurement error-some contact resistance

CONCLUSIONS

An endurance test of an SPT- 100 was performed for 6,925 on/off cycles and 5,730.3 hours of operation at an input power of 1.35 kW. The endurance test was initiated July 1, 1993 and ended on November 21, 1994. The nominal cycle duration was 50 minutes on and 23 minutes off, including nearly three minutes of cathode preheat time. The SPT-1OO was powered by the Loral breadboard PPU. The original test objectives, to demonstrate SPT- 100 cyclic operation for 6,000 cycles and 5,000 hours, were exceeded. The wear test was extended to accumulate additional cycles and operating hours on cathode #l. A total of 6,051 cycles and 5,002.5 hours of operating time were accumulated on cathode #1, then the wear test was voluntarily terminated.

Thruster efficiency decreased, from 50% to 42% as the thruster aged; thruster efficiency increased between cycles 1,000-3,000, then decreased slightly over the remaining duration of the wear test. Current and voltage oscillations increased, then decreased to levels near what they were at the start of the wear test. No significant changes in the thruster plume were observed between the start and end of the wear test.

The insulators forming the discharge chamber walls were heavily eroded, as expected based on Russian wear test experience. The most surprising result of the wear test is that in this thruster design, the unused cathode igniter erodes at an extremely high rate. The primary failure mechanism for this thruster is that material eroded in the unused cathode could short-circuit the igniter to the emitter.

A short developed between the cathode igniter and the emitter at cycle 5,316, and after 5,316 cycles and 4,393.5 hours of operation the thruster was started and operated on cathode. #2. The only noticeable difference in thruster operation between the two cathodes was a higher floating voltage on cathode #2. The short was physically cleared when the vacuum tank was opened after cycle 6,346, then the thruster was operated on cathode #1 until over 5,000 hours were accumulated on that cathode.

Thruster operating characteristics such as propellant con sun iption rate, thrust and floating voltage for the last cycle in the wear test were stable, despite significant wear in the thruster insulators and thruster body. Based on performance characteristics demonstrated in this wear test the SPT- 100 is fully adequate to perform NSSK functions for large commercial communication satellites.

ACKNOWLEDGMENTS

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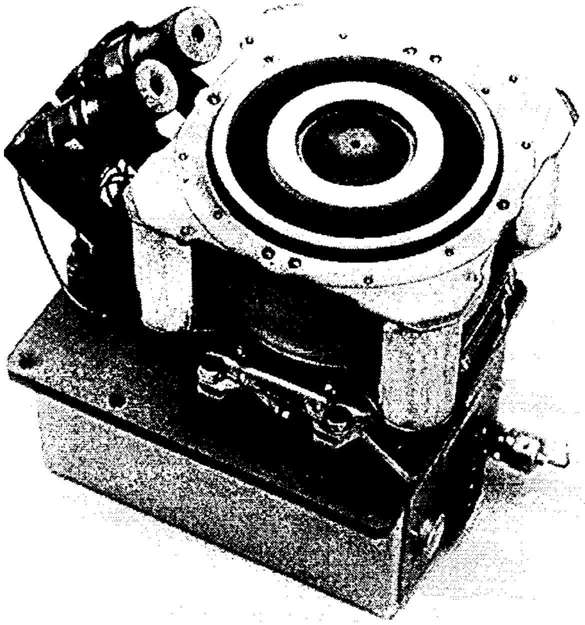

Fig. 1. New SPT-100 as tested.

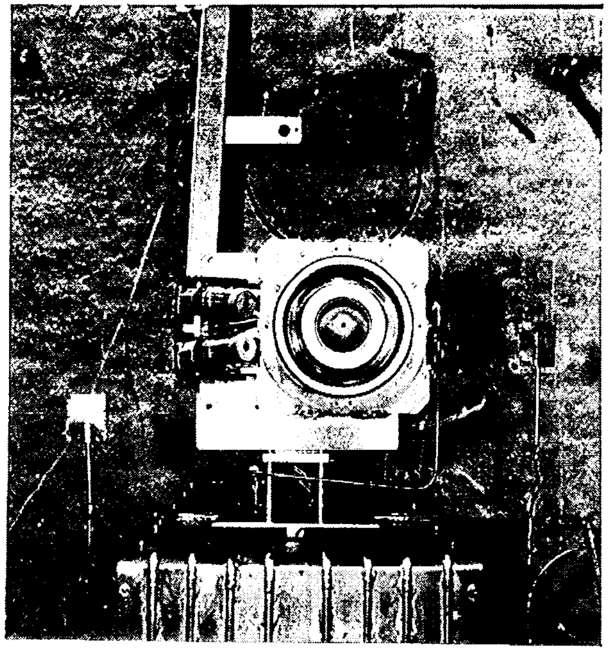

Fig. 2. SPT-100 installed on water-cooled thrust stand.

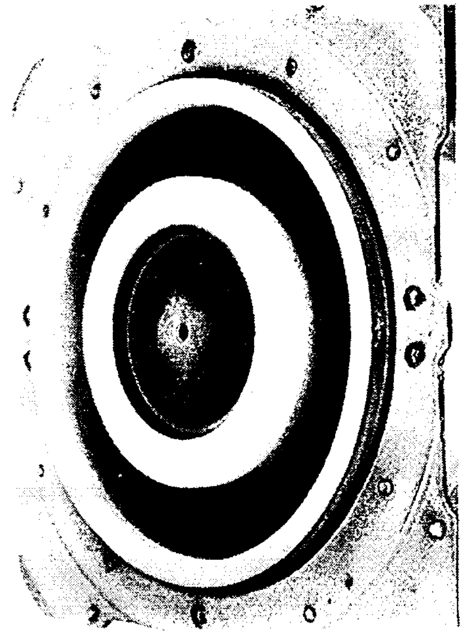

Fig. 3. SPT-100 from an off-axis view.

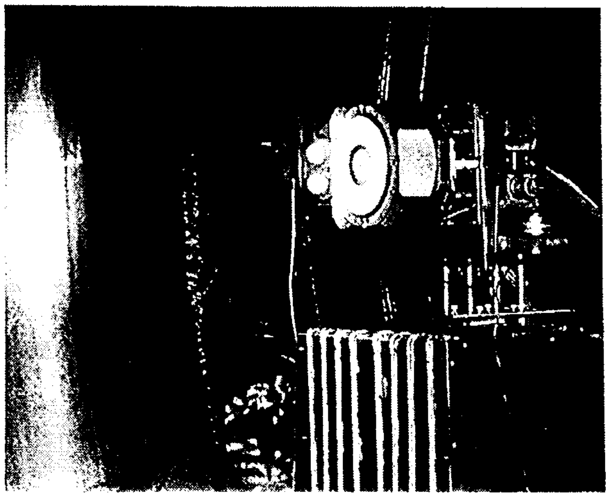

Fig. 4. SPT-100 operating in the JPL life test facility.

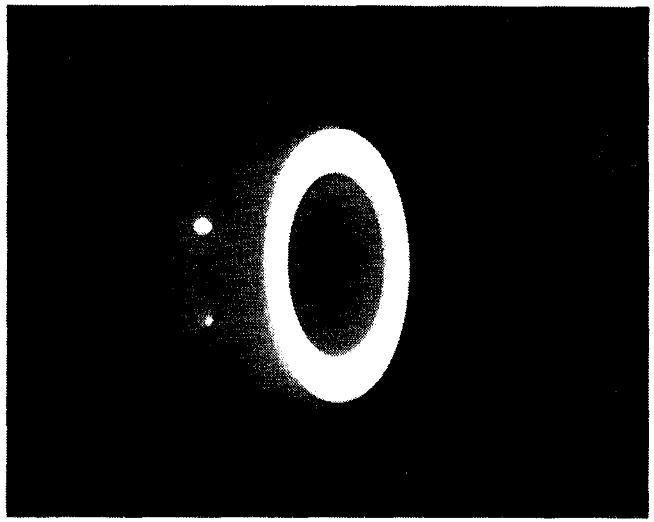

Fig. 5. Glow in unused (bo thod

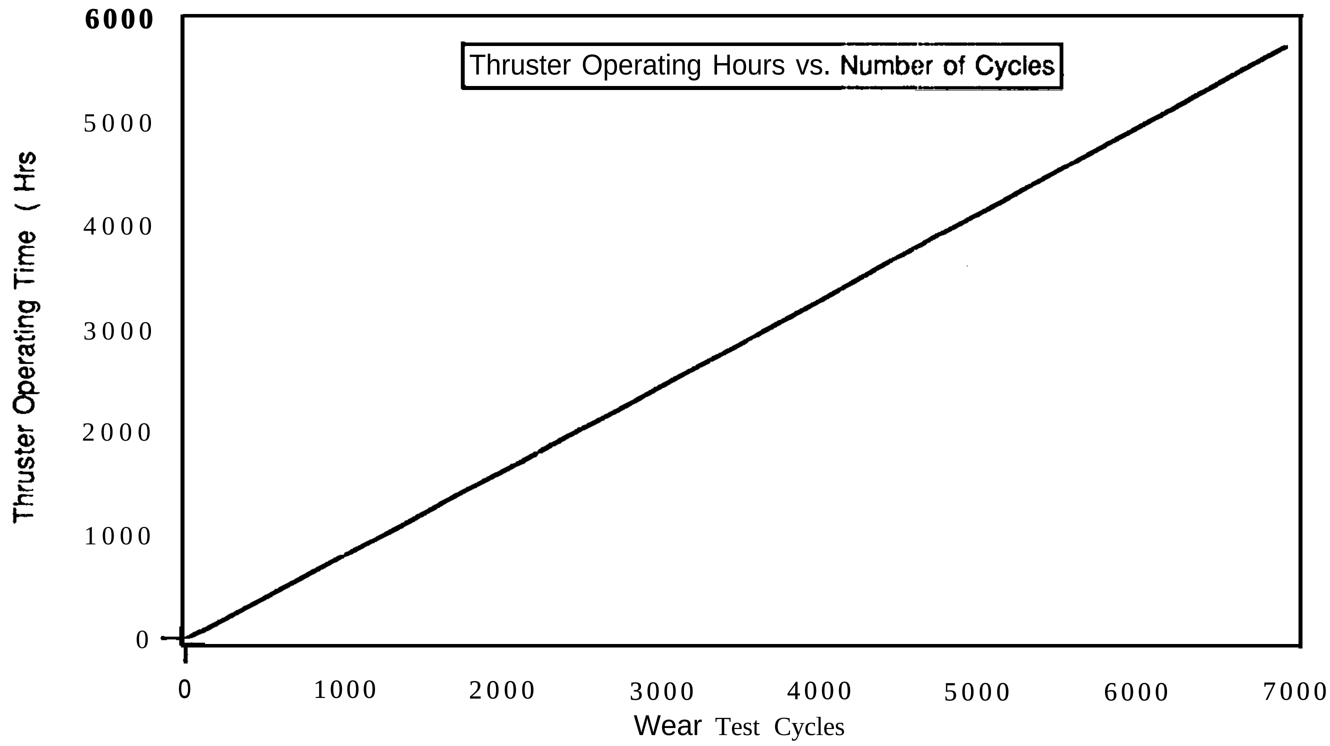

Fig. 6. Thruster **operating** hours vs. wear test cycles.

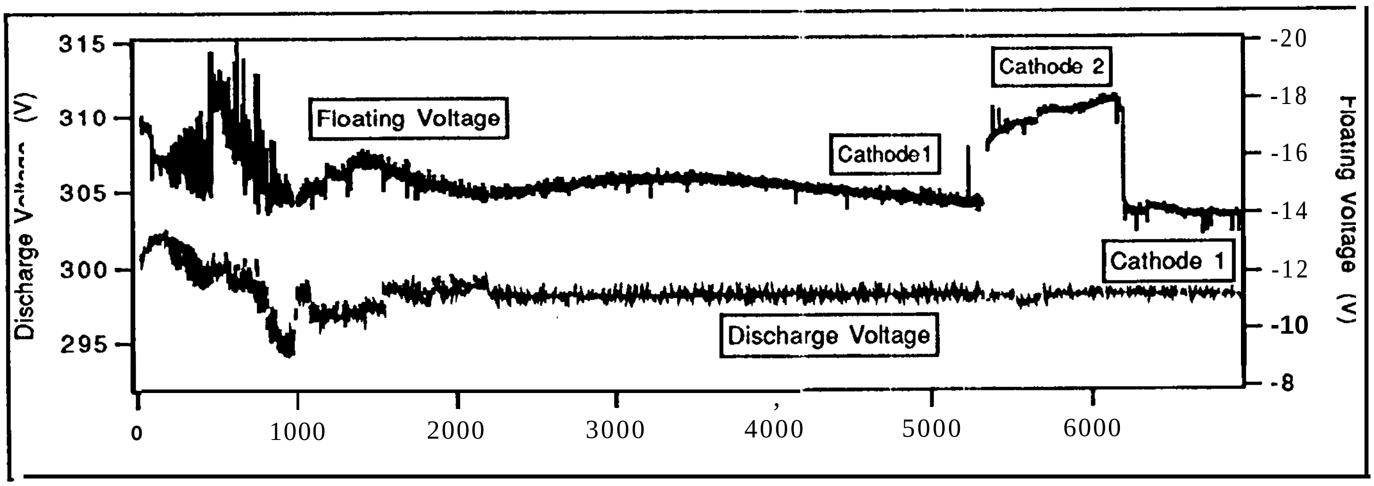

Fig. 7. **Discharge** voltage **and** floating voltage for all wear test cycles.

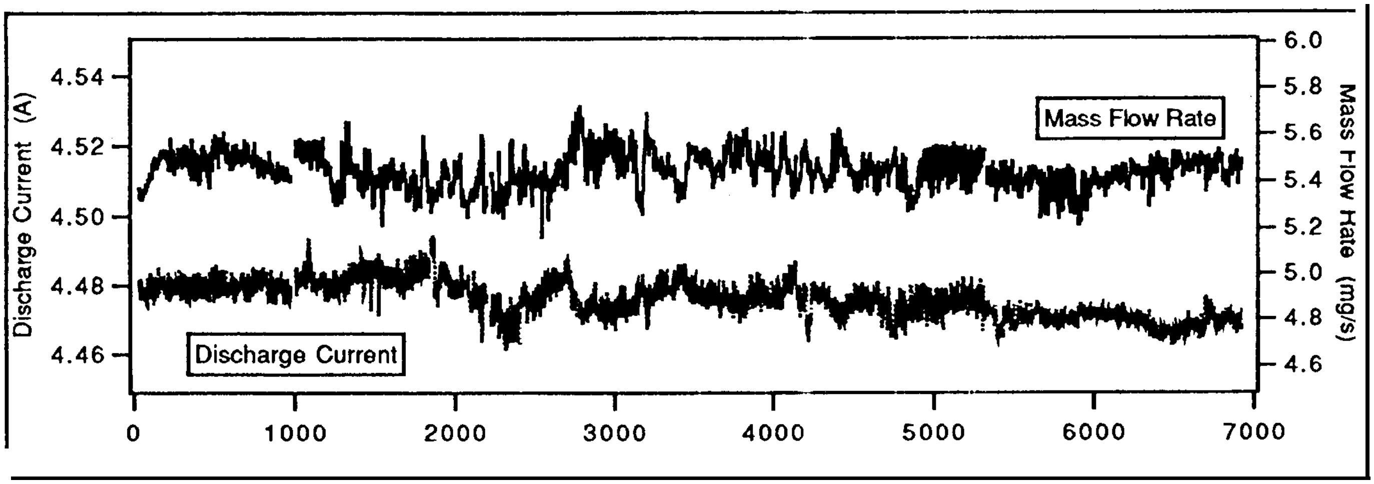

Fig. 8. Mass flow rate and discharge current for all wear test cycles.

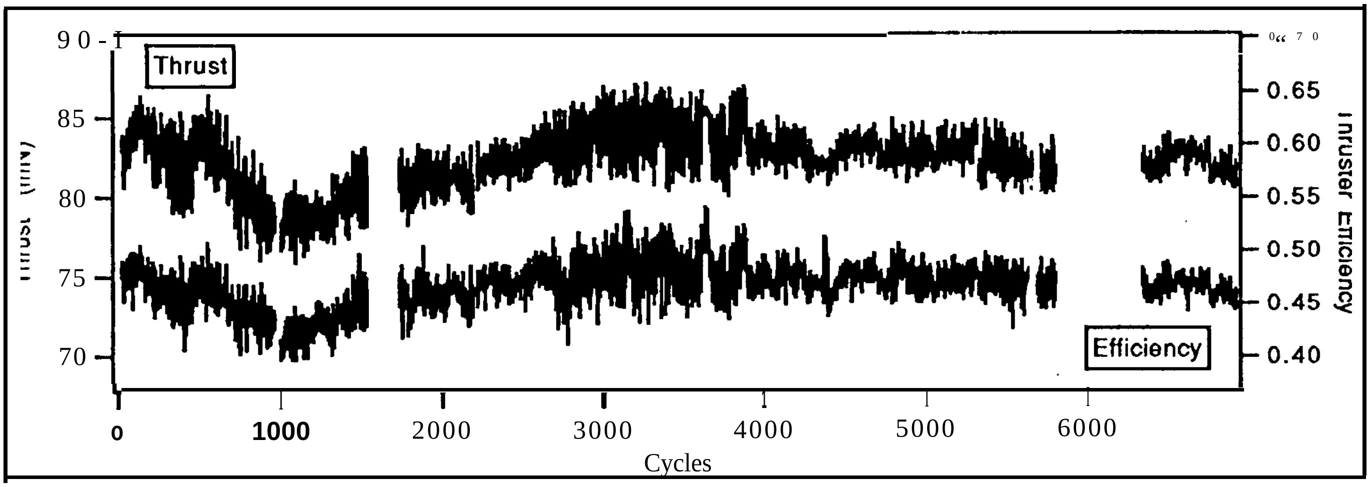

Fig. 9. Thrust and efficiency for all wear test cycles.

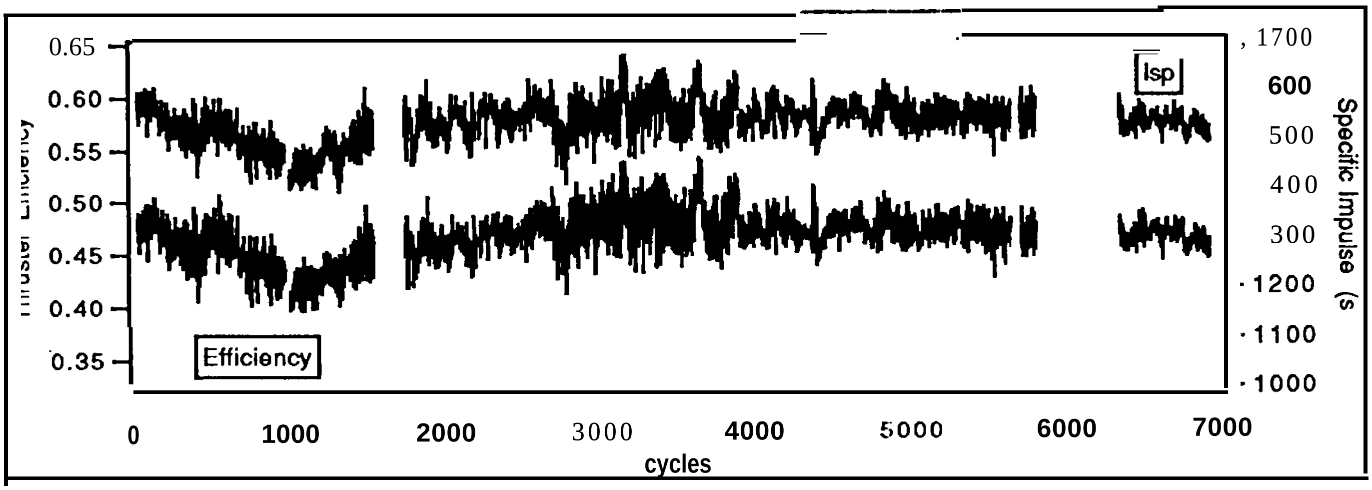

Fig. 10. Thruster efficiency and specific impulse for all wear test cycles.

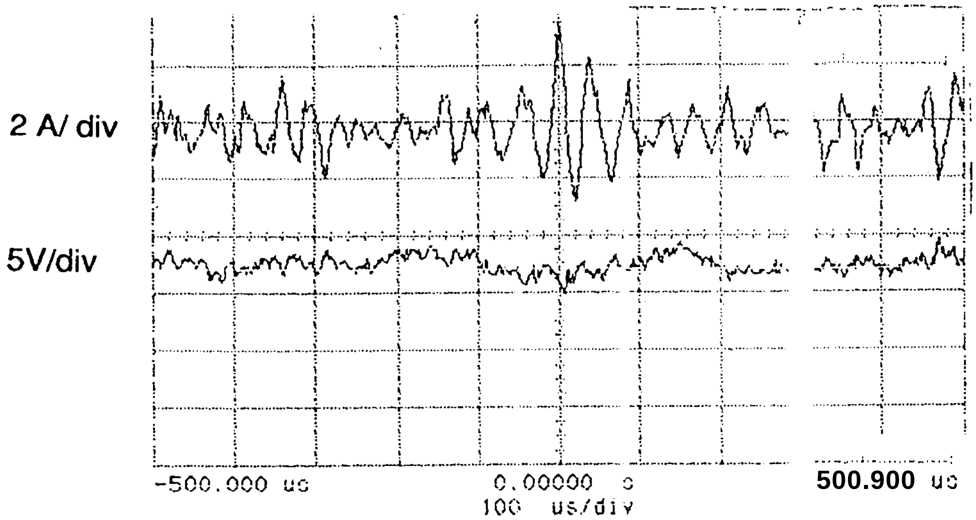

Fig. 1 la. Oscillations in the discharge current and voltage for cycle 27.

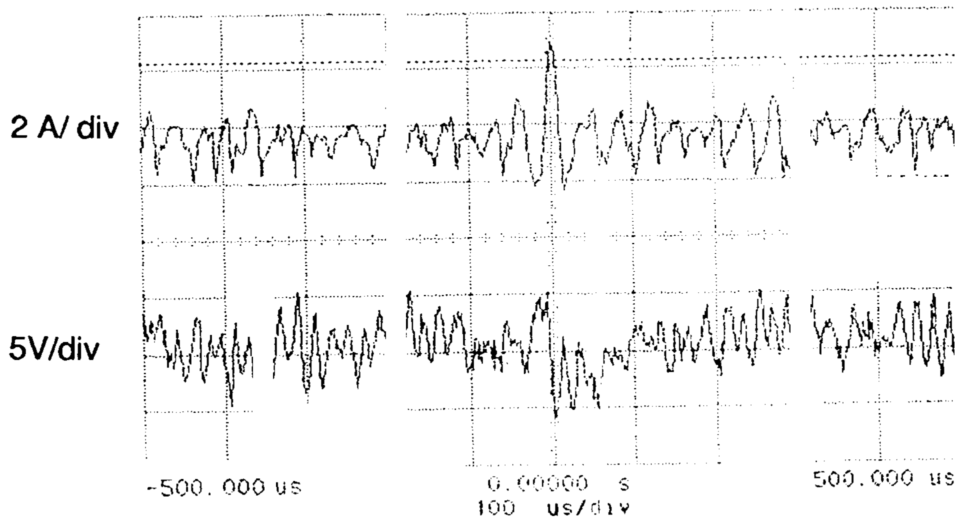

Fig. 1 lb. Oscillations in the discharge current and voltage for cycle 6,925.

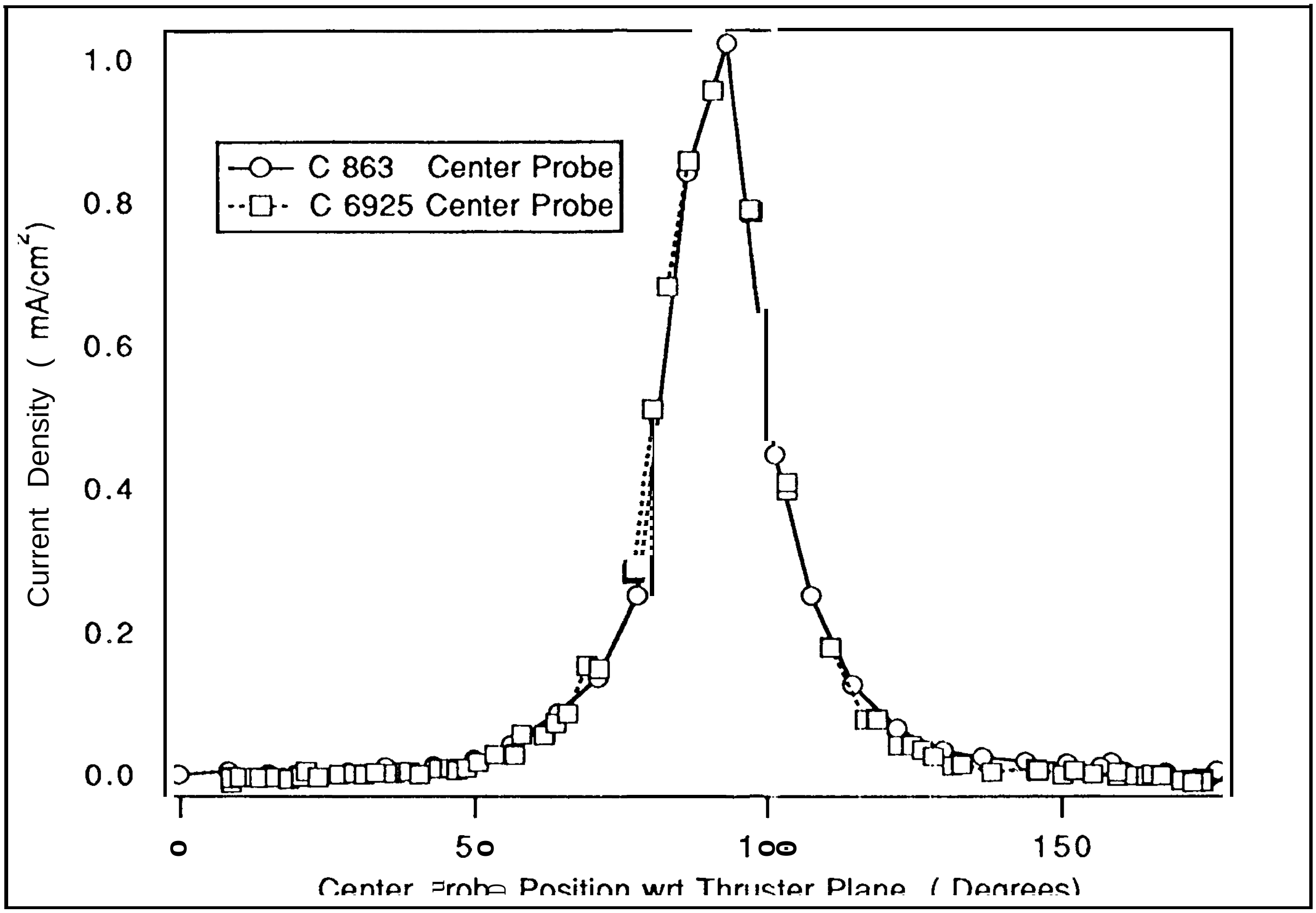

Fig. 12. SPT-100 plume characteristics.

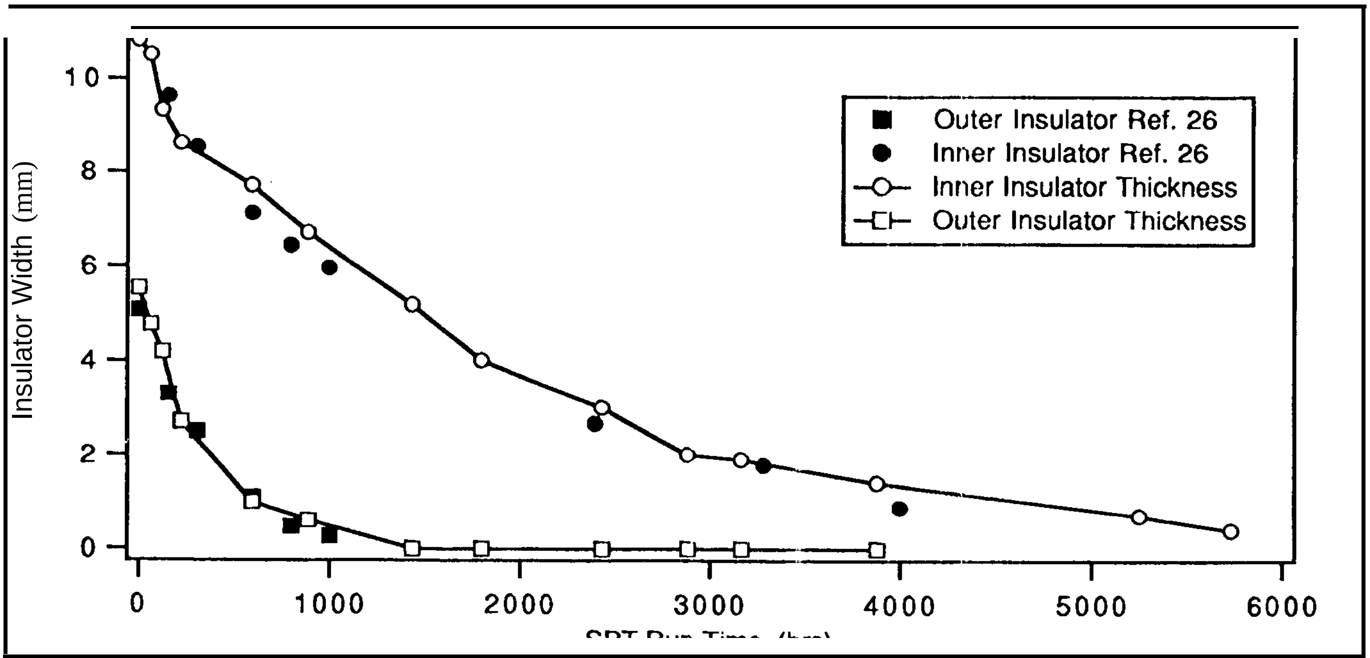

Fig. 13. Insulato erosion as a function o time.

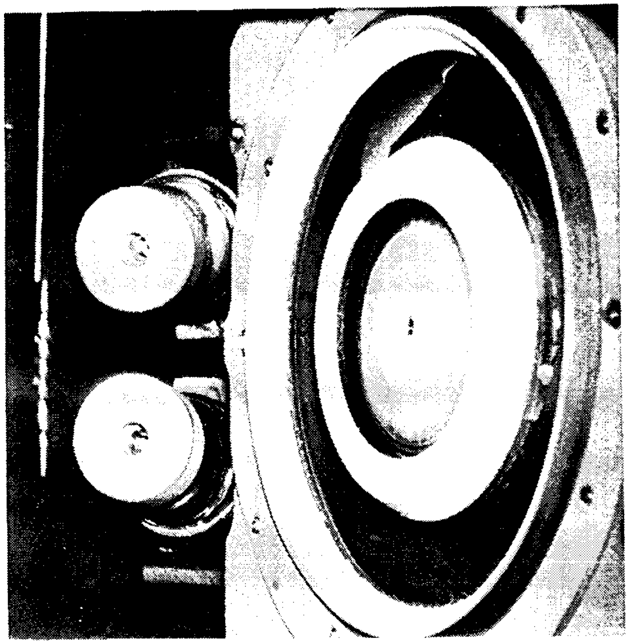

Fig. 14. SPT-100 at 740 cycles and 595 hours of operation.

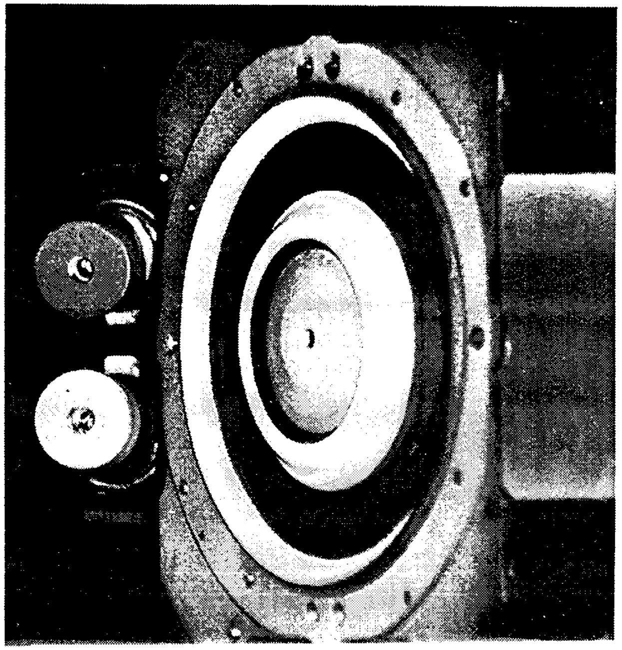

Fig. 15. SPT-100 at 1690 cycles and 1378.2 hours.

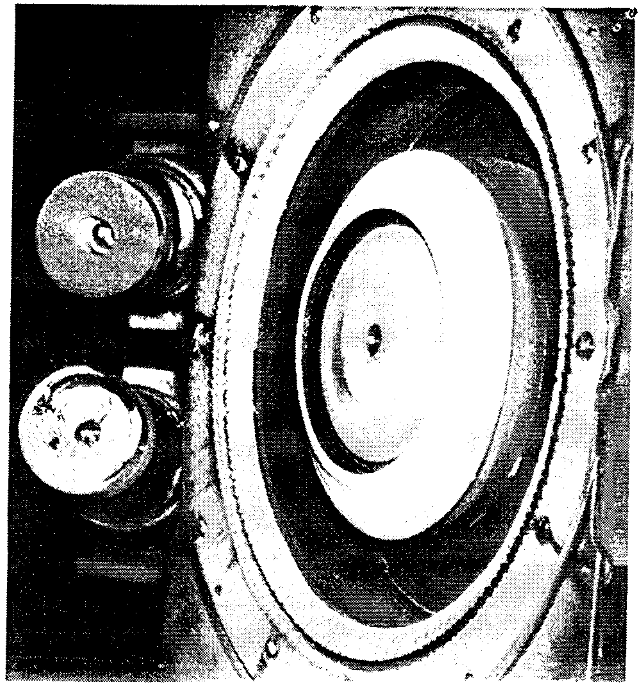

Fig. 16. SPT-100 at 3816 cycles and 3139.2 hours.

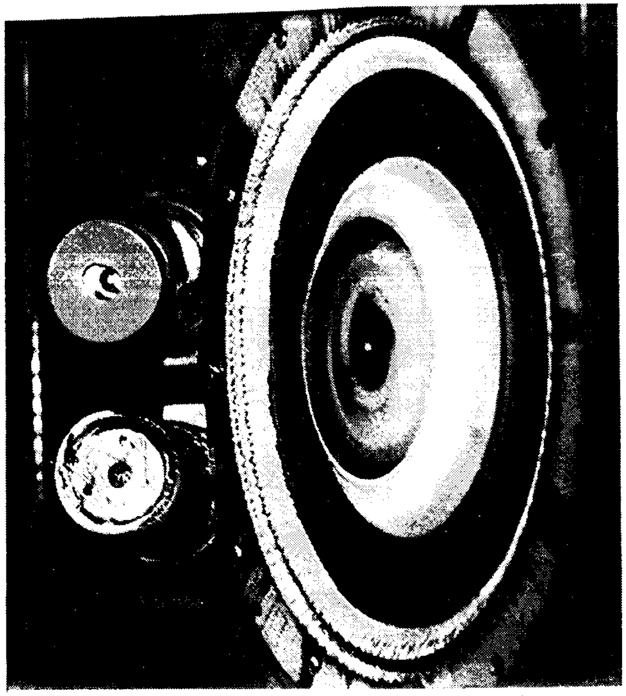

Fig. 17. SPT-100 at 4702 cycles and 3881.4 hours.

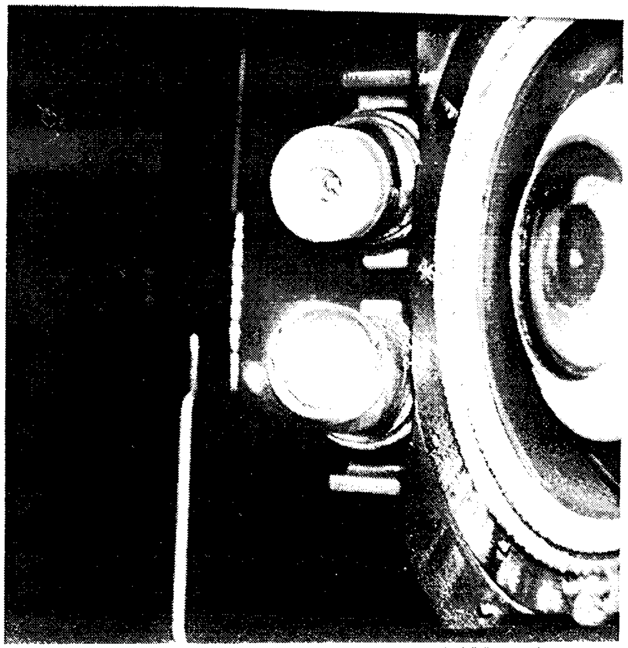

Fig. 18. SPT-100 at 5321 cycles and 4397.7 hours.

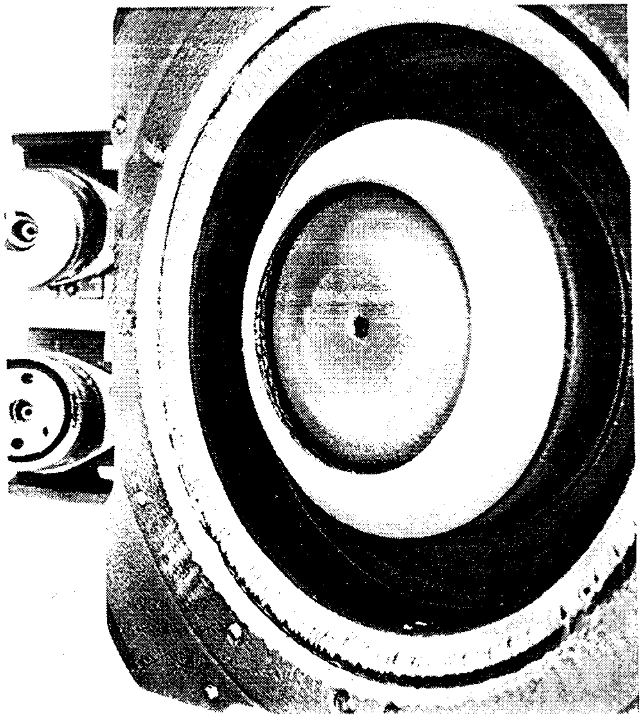

Fig. 19. SPT-100 at 6925 cycles and 5730 hours.

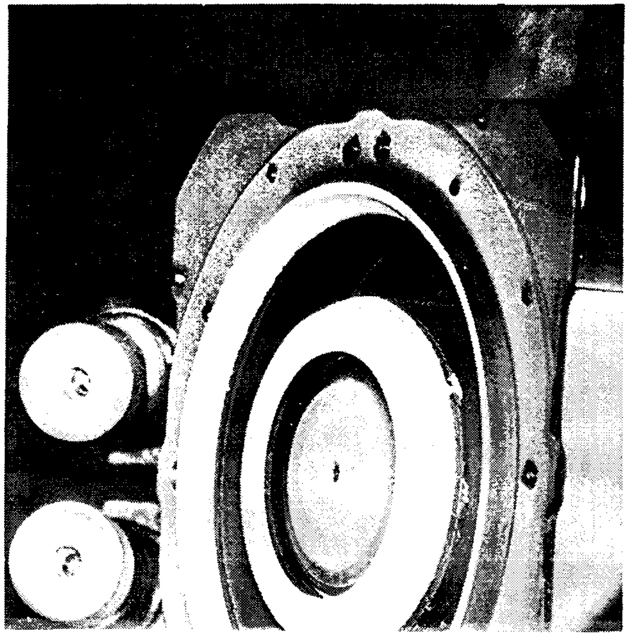

Fig. 20. Cathode erosion after 556 cycles and 445.5 hours.

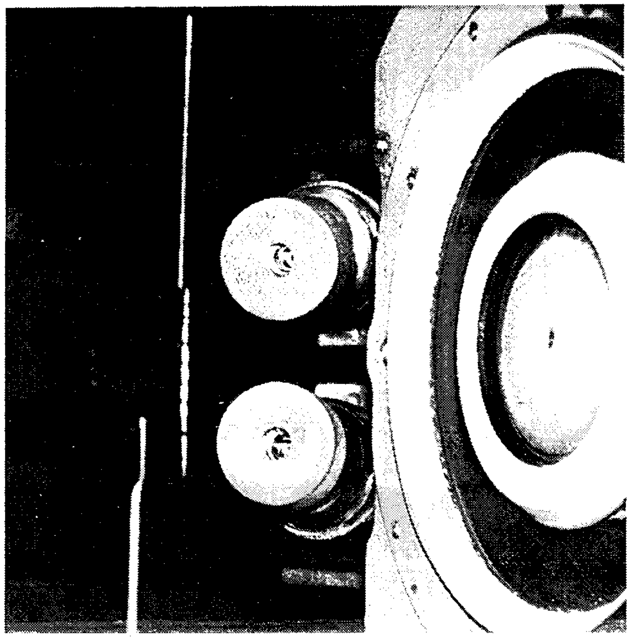

Fig. 21. Cathode erosion after 866 cycles and 698.7 hours.

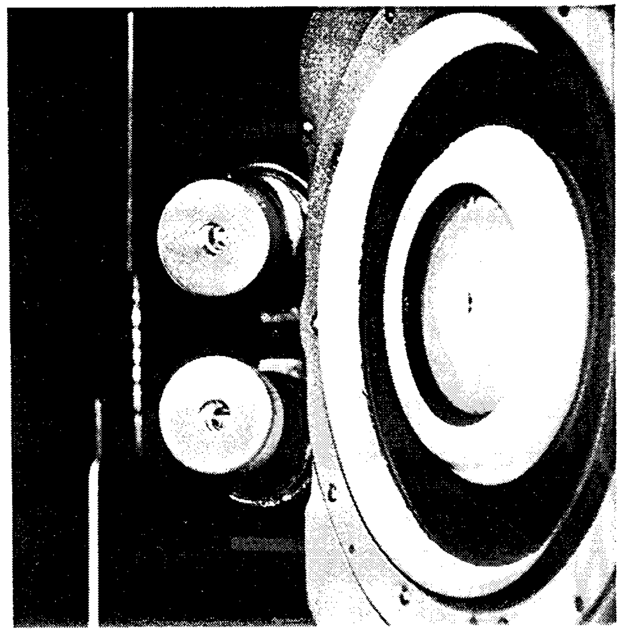

Fig. 22. Cathode erosion after ,099 cycles and 890.6 hours.

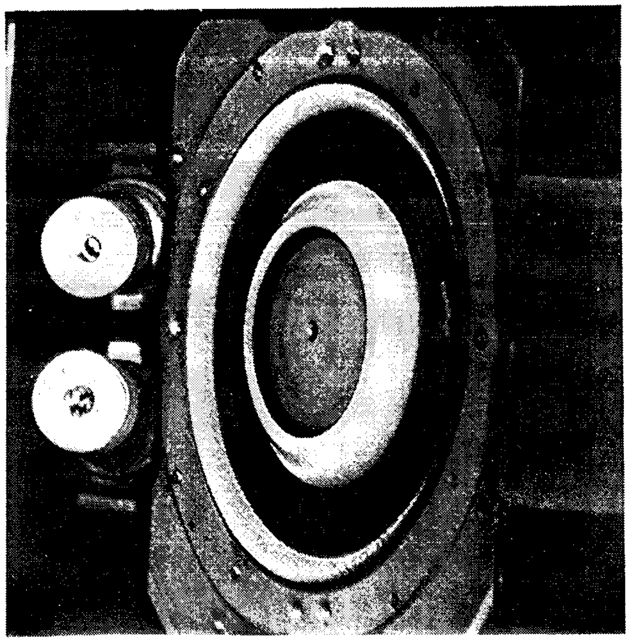

Fig. 23. Cathode erosion after 2,202 cycles and 1,795.8 hours.

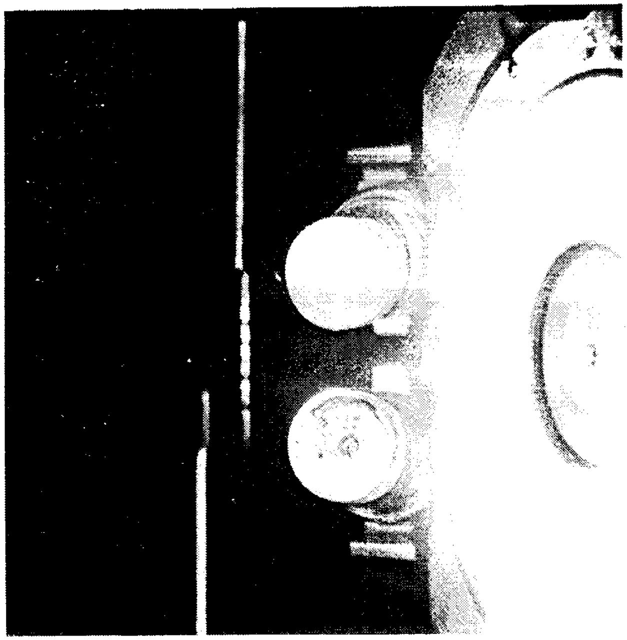

Fig. 24. Cathode erosion after 3,003 cycles and 2,462.9 hrs.

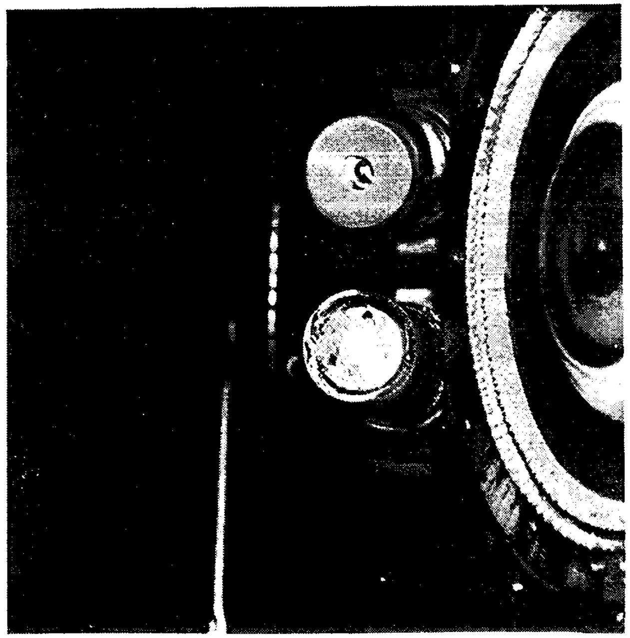

Fig. 25. Cathode erosion after 5,321cycles and 4,397.7hrs.

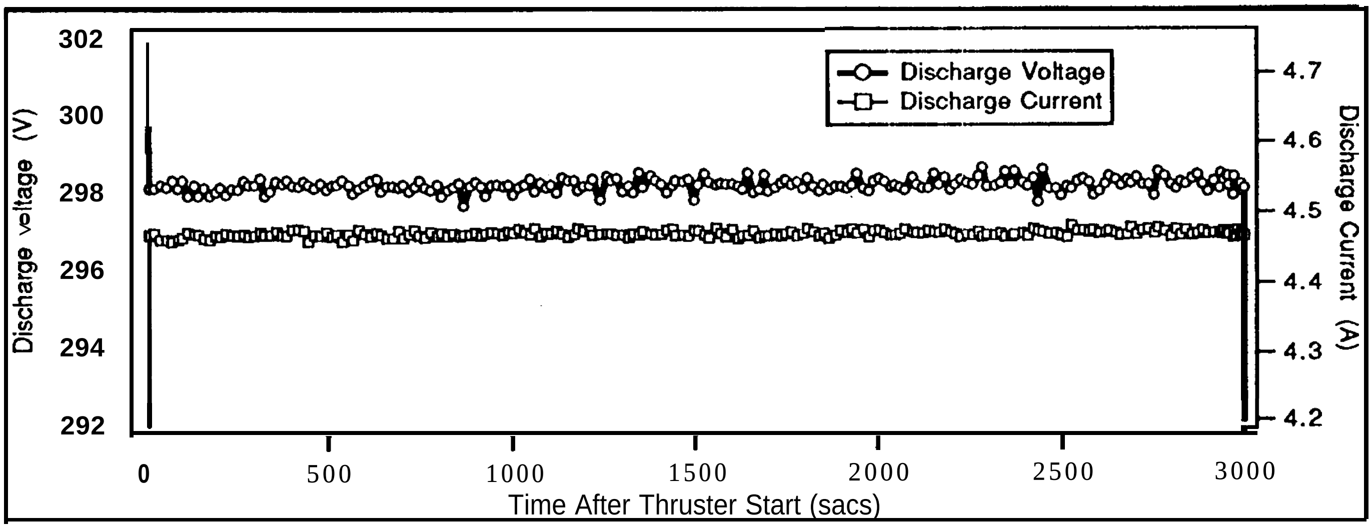

Fig. 26. **Discharge current and** voltage for cycle 6,925.

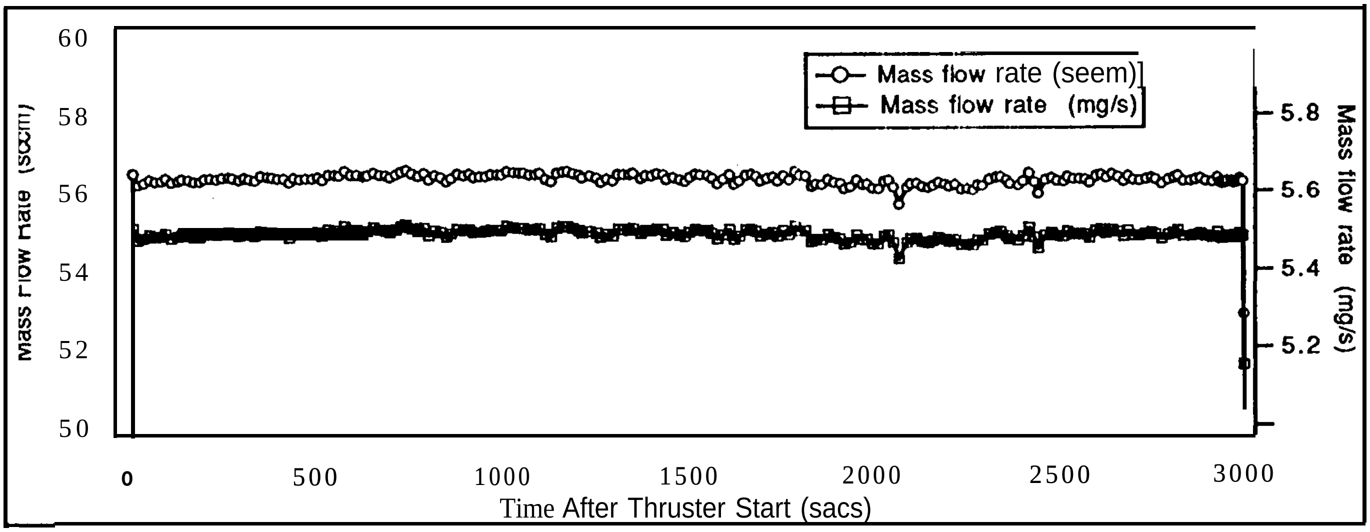

Fig. 27. Mass flow rate and discharge current for cycle 6,925.

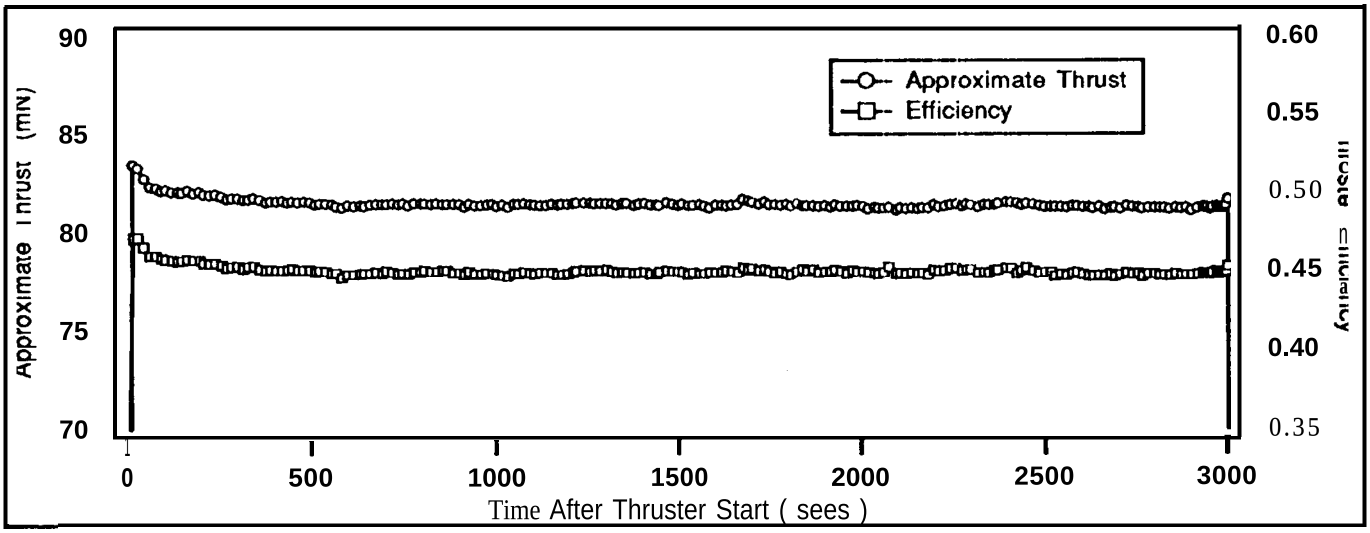

Fig. 28. Approximate thrust and efficiency for cycle 6,925. Higher thrust levels measured during the first approximately 200 seconds of the cycle are due to changes in the thrust stand inclination

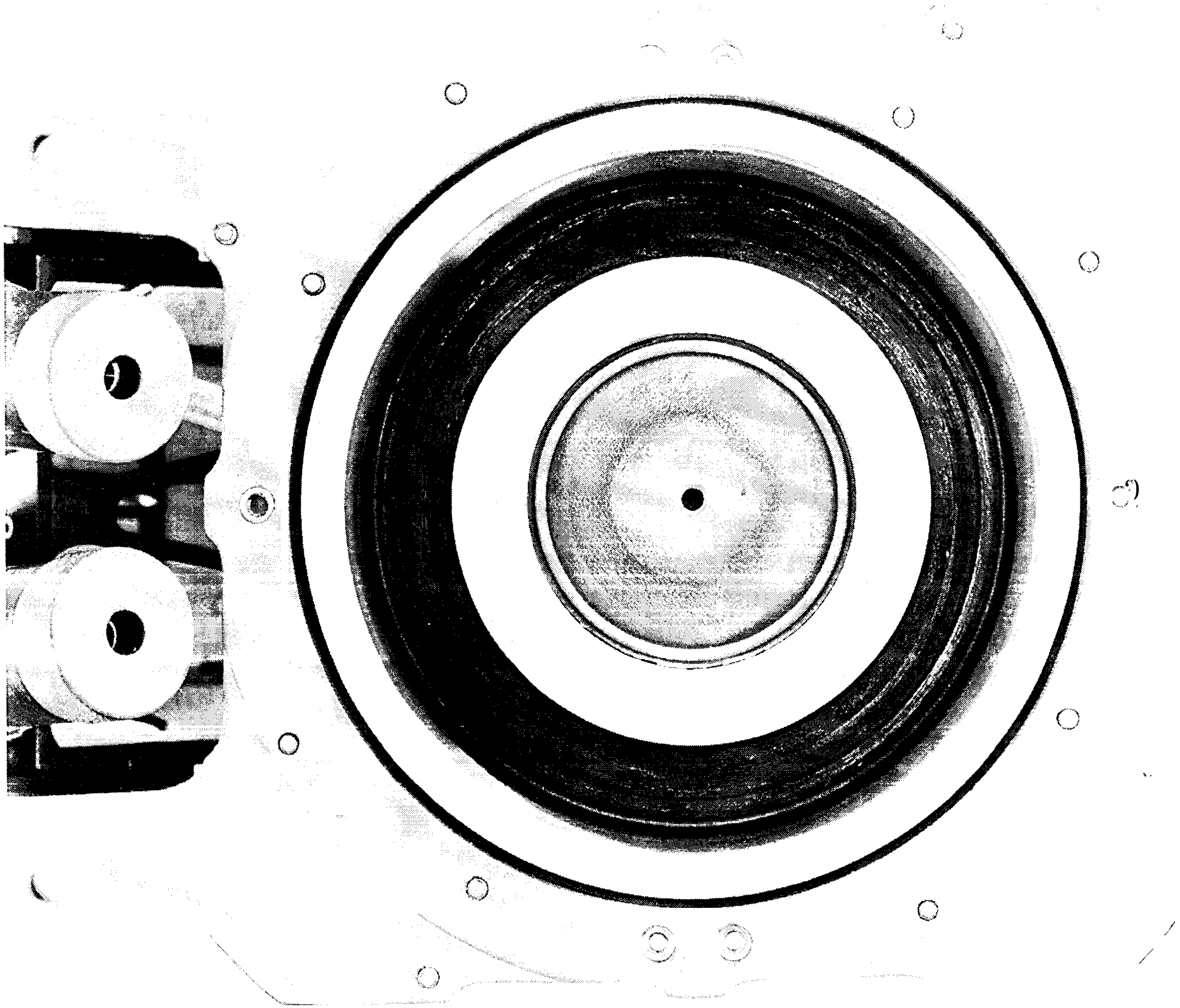

Fig. 29. Photograph of the SPT- 100 before start of the wear test.

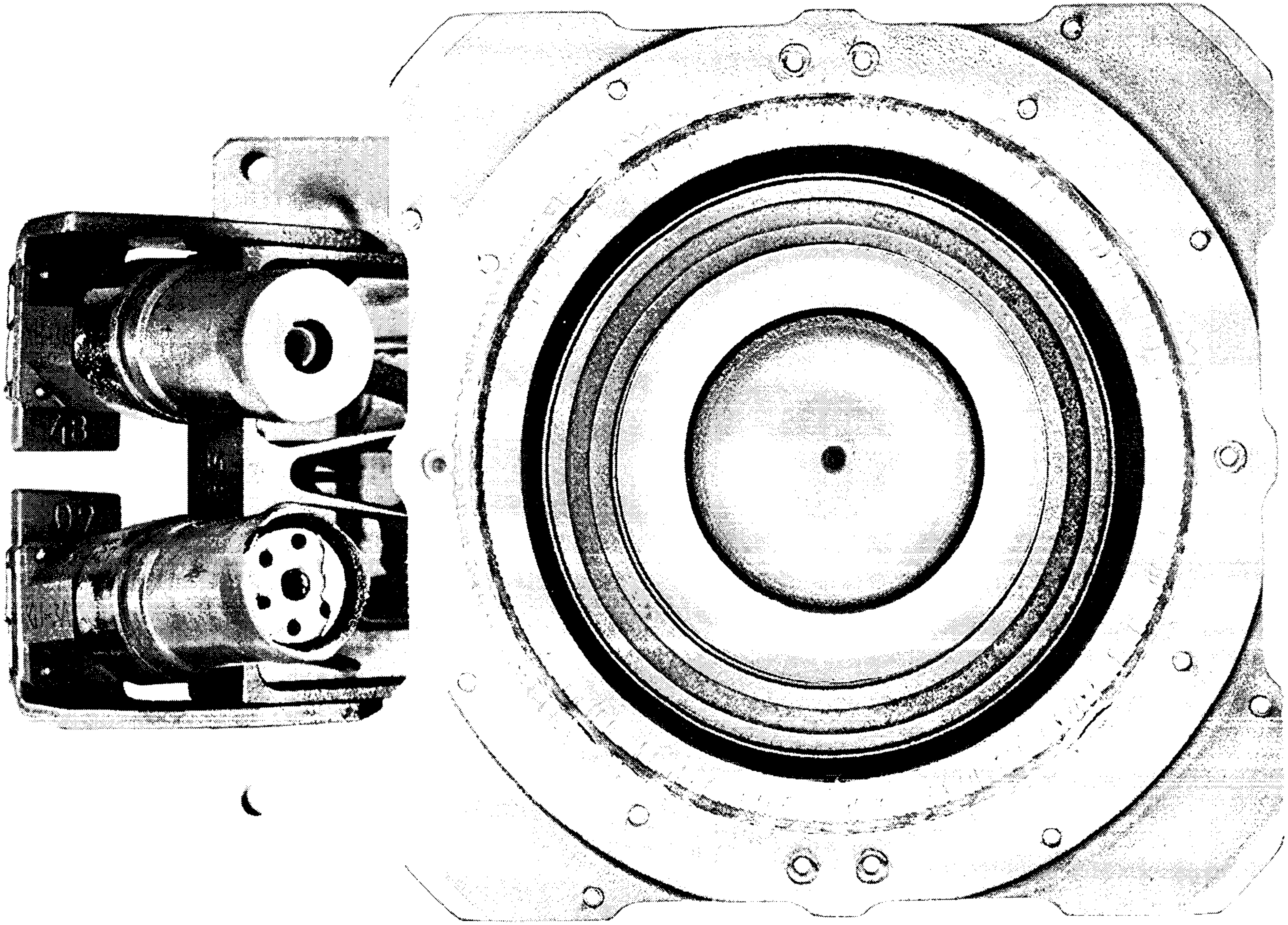

Fig. 30. Photograph of the SPT-100 after 6,925 cycles and **5,730,3** hours of wear testing. Note the holes in the thruster body at locations adjacent to the electromagnets.

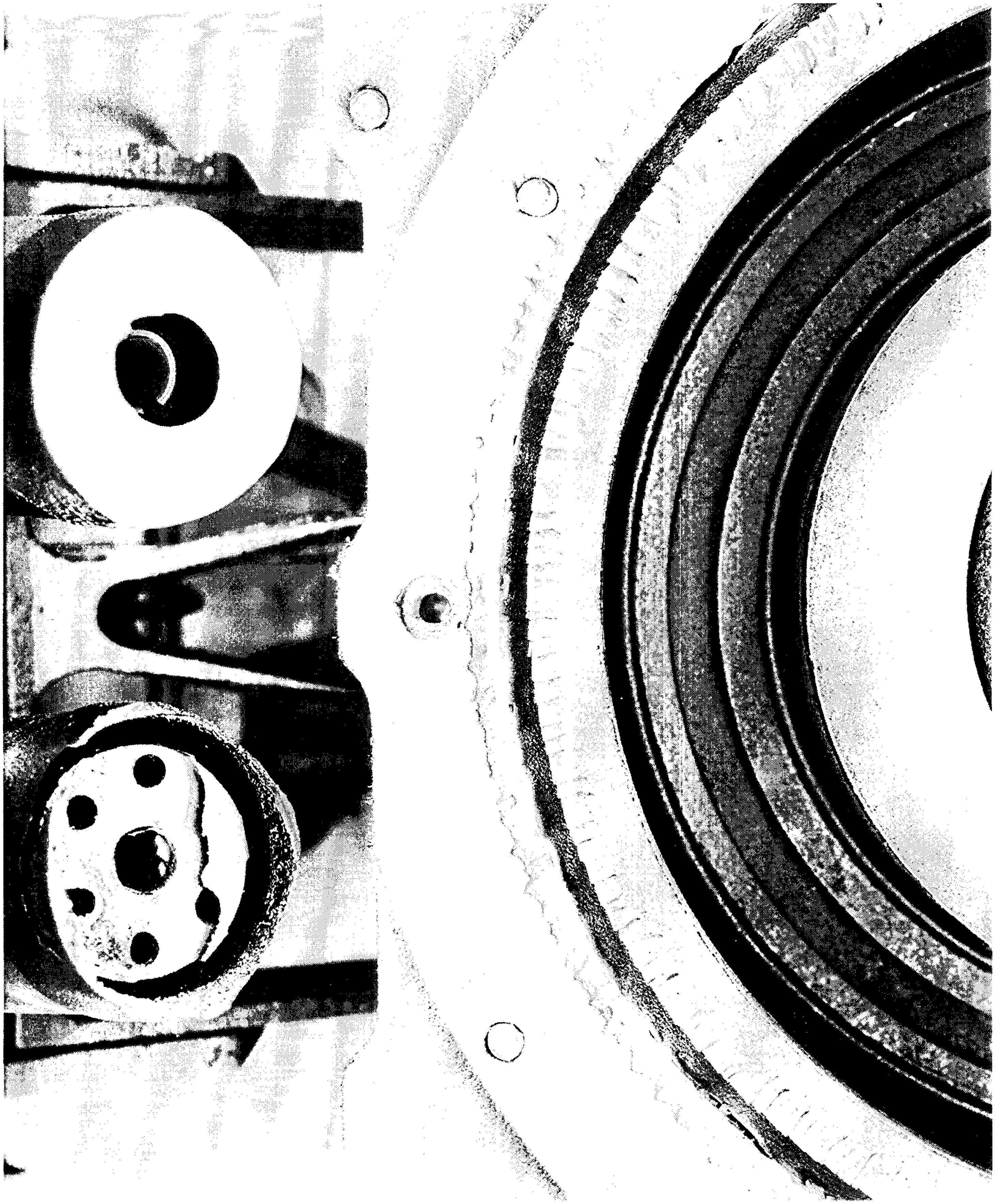

Fig. 31. Close-up view of the outer insulator, thruster body, and the thruster cathodes. Note the holes in the thruster body at locations adjacent to the electromagnets. Cathode #1 (the primary cathode) is at the top.

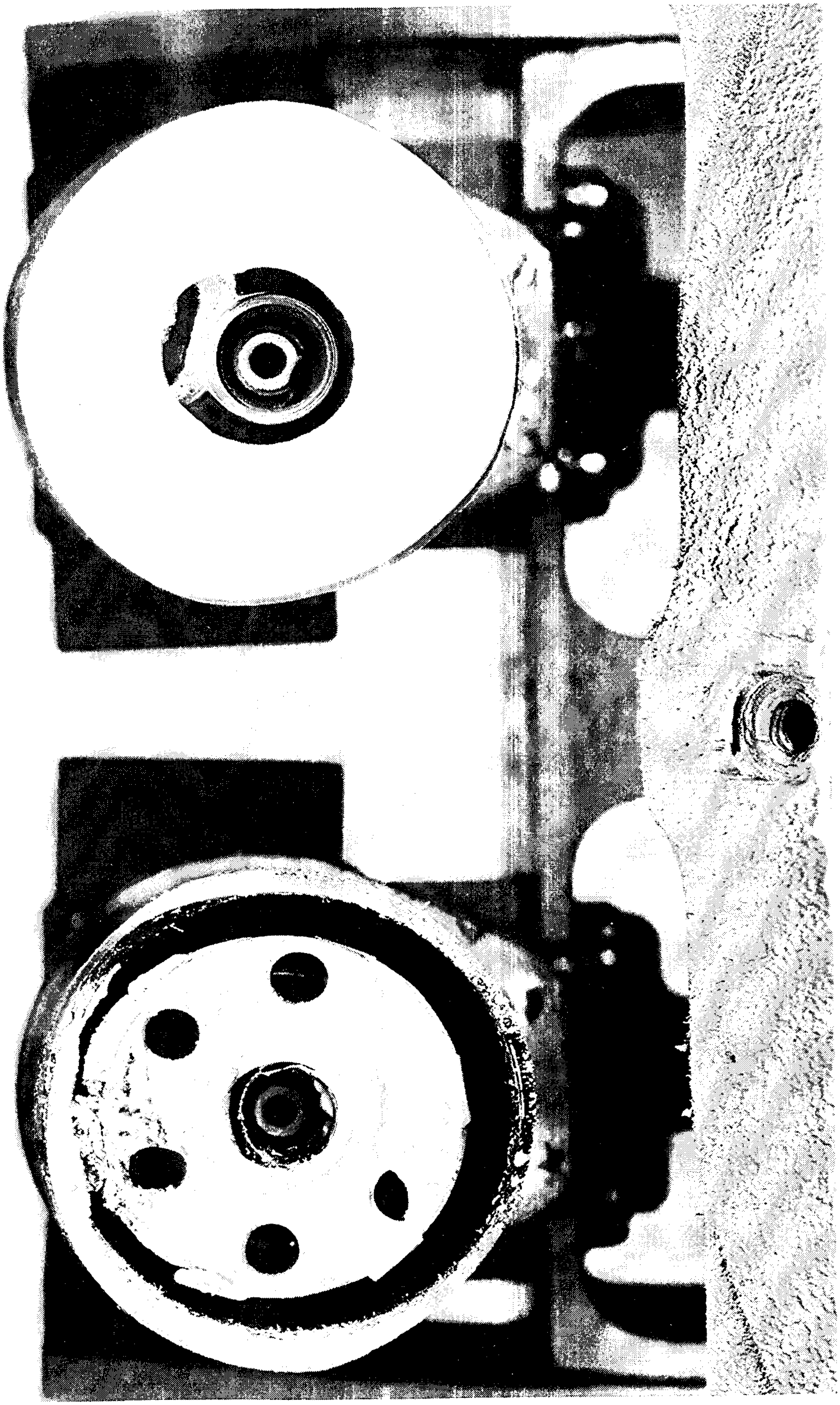

Fig. 32. Close-up view of cathode #1(top) and cathode #2 (bottom).